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VTT  
<http://www.vtt.fi>  
P.O. box 1000FI-02044 VTT  
Finland

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## Calibration of Abaqus CDP model parameters

Kim Calonius<sup>1</sup>, Alexis Fedoroff<sup>1</sup>, Kari Kolari<sup>1</sup>, Reijo Kouhia<sup>2</sup> and Jani Vilppo<sup>2</sup>

<sup>(1)</sup>VTT Technical Research Centre of Finland, Ltd., `firstname.lastname@vtt.fi`

<sup>(2)</sup>Tampere University, `firstname.lastname@tuni.fi`

**Summary.** This article proposes a relaxed strategy for the calibration of the Abaqus Concrete Damaged Plasticity (CDP) model in order to avoid the use of computationally expensive optimization techniques.

*Key words:* Concrete Damaged Plasticity (CDP), model calibration, Abaqus

### Introduction

The Concrete Damaged Plasticity (CDP) built-in material model available in the Abaqus commercial finite element software, [1], is widely used for beyond design criteria analyses of reinforced concrete structures within the Abaqus users community. In particular, the CDP model has proven to be versatile enough to be used in beyond design basis earthquake analyses, [2, 3, 4], as well as in benchmark impact test analyses, [5, 6, 7], and full scale airplane crash simulations, [8].

Originally developed on top of the “Barcelona” yield surface, [9], and later on the isotropic hardening laws proposed by Lee and Fenves, [10, 11], that separate the internal plastic variables into a tensile and a compressive parts, the CDP model in Abaqus enables also field variable dependent customized approaches. For example, a user enhanced Abaqus CDP model with confinement stress dependent compressive hardening evolution and strain rate dependent tensile softening evolution was proposed in [12]. Such custom material models are, indeed, necessary in special applications, in case of the previous example, in hard missile impact simulations.

### Material model calibration as an optimization problem

Formally, the material model calibration is an optimization problem: “For a given material defined by its physical properties,  $X_{\text{exp}}$ , find material model input data,  $X_{\text{sim}}$ , such that the distance between the experimental test output data,  $Y_{\text{exp}} = \mathcal{T}(X_{\text{exp}})$ , and the simulated test output data,  $Y_{\text{sim}} = \mathcal{S}(X_{\text{sim}})$ , is minimum.” Figure 1 shows the mapping diagram relative to material model calibration. One can, therefore, consider the formal (constrained) minimization problem of with the following objective function:  $F(X_{\text{sim}}) = \text{dist}(\mathcal{T}(X_{\text{exp}}), \mathcal{S}(X_{\text{sim}}))$ .

The fundamental difficulty which arises in the context of concrete modeling, is that the physical properties of a given material, such as cement chemical composition and aggregate size distribution, are totally unrelated to the material model input data. In case of the Abaqus CDP model the material input data is a collection of elasto-damage-plasticity parameters that define the elastic properties, the initial shape of the yield surface and its evolution with the increase of the internal hardening variables. On the other hand, the mechanical properties of concrete defined in the Eurocode and the FIB model code, [13, 14], are values that depend on the experimental setup such as sample size, boundary conditions and loading speed. Typically, the concrete material experiment set includes uniaxial monotonic or cyclic compression tests to

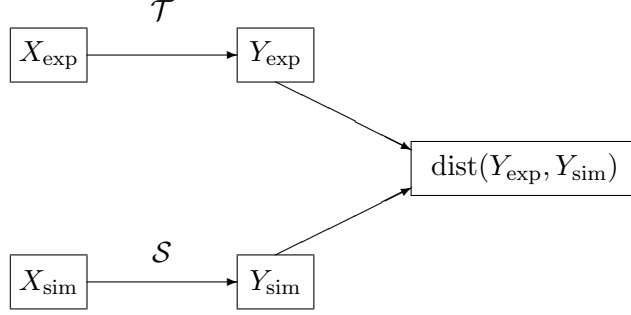


Figure 1. The basic structure of material model calibration.

determine elastic and compressive behavior and three point bending tests on notched specimen as well as split tensile tests to determine tensile behavior. In addition, the experiment set may include triaxial and/or biaxial tests to determine the failure surface shape and confinement dependency, as well as tensile and compressive split Hopkinson pressure bar tests to determine loading rate sensitivity.

Table 1. Mechanical material parameters for concrete defined in Eurocode

Denomination	Symbol	Unit
Compressive peak strength	$f_{cm}$	(MPa)
Total strain at compressive peak strength	$\epsilon_{c1}$	(%)
Tensile peak strength	$f_{ctm}$	(MPa)
Fracture energy	$G_f$	(N/m)
Secant modulus of elasticity	$E_{cm}$	(MPa)
Poisson ratio	$\nu_{cm}$	(-)
Confinement increase factor for compressive stress	CIF	(-)
Dynamic increase factor for tensile stress	DIF <sub>f</sub>	(-)
Dynamic increase factor for tensile fracture energy	DIF <sub>g</sub>	(-)
equibiaxial to uniaxial initial yield ratio	$\sigma_{b0}/\sigma_{c0}$	(-)
tensile to compressive meridians slope ratio	$K_c$	(-)

Therefore, it would be a mistake to consider the Eurocode mechanical concrete properties as intrinsic material parameters that can be mapped one-to-one to the material model parameters. Nevertheless, by comparing the contents of Table 2 and Table 1, one can conclude that at least some of the Eurocode mechanical concrete properties can be used as an initial guess,  $X_{sim}^{(0)}$  for the minimization problem defined by the objective function  $F$ . On the other hand, it is clear that carrying out all the experiments cited above is a tough requirement. Therefore, one has to figure out a relaxed strategy to calibrate the material model with fewer experimental results.

### Relaxed strategy for material model calibration

The proposed relaxed strategy for the CDP material model calibration relies on the assumption that not all of the material model parameters mentioned in Table 2 are equally important. To define the most important material parameters, the sensitivity of the model to the material parameters was studied first. Based on observations of the model behavior, an iteration order for material test simulations is proposed as per Table 3. For each simulation, model parameters to be determined by iteration as well as fixed parameters are prescribed. The value for a given

Table 2. CDP model input parameters

Denomination	Symbol		Expression
Elastic stiffness modulus	$E$	$\approx$	$E_{\text{cm}}$
Elastic Poisson ratio	$\nu$	$\approx$	$\nu_{\text{cm}}$
Yield surface shape parameter	$\alpha$	$=$	$(\sigma_{b0}/\sigma_{c0} - 1)/(2\sigma_{b0}/\sigma_{c0} - 1)$
Yield surface shape parameter	$\gamma$	$=$	$(3(1 - K_c))/(2K_c - 1)$
Uniaxial compressive hardening function	$\sigma_c(\epsilon_c^p)$	$=$	$\sigma_{c0}((1 + a_c)e^{-b_c \epsilon_c^p} - a_c e^{-(1+k)b_c \epsilon_c^p})$
Uniaxial tensile hardening function	$\sigma_t(\epsilon_t^p)$	$=$	$\sigma_{t0} e^{-b_t \epsilon_t^p}$
Uniaxial initial compressive yield stress	$\sigma_{c0}$	$\approx$	$0.4 \text{ CIF } f_{\text{cm}}$
Uniaxial initial tensile yield stress	$\sigma_{t0}$	$\approx$	$\text{DIF}_f f_{\text{ctm}}$
Characteristic length	$l_{\text{ch}}$	$\approx$	average element dimension
Characteristic fracture energy	$g_F$	$=$	$\text{DIF}_g G_F/l_{\text{ch}}$
Ratio	$\mu$	$=$	$\max \sigma_c/\sigma_{c0}$
Compressive hardening parameter	$a_c$	s.t.	$k^k (1 + a_c)^{1+k} - (1 + k)^{1+k} \mu^k a_c = 0$
Compressive hardening parameter	$b_c$	$=$	$-\frac{1}{k \arg\max \sigma_c} \ln \frac{1+a_c}{(1+k)a_c}$
Compressive hardening parameter	$k$	$\in$	$\{1, 2, 3, \dots\}$
Tensile hardening parameter	$b_t$	$=$	$\sigma_{t0}/(g_F + \frac{1}{2}(\sigma_{t0})^2/E)$
Dilation angle	$\phi$		
Eccentricity of Drucker-Prager hyperboloid	$e$		

fixed parameter is obtained from an appropriate simulation result on the previous iteration round. If there is no appropriate simulation result available, then an Eurocode value is applied as suggested by Table 2.

Table 3. Material test simulation iteration order

Order	Simulation	Parameter to be iterated	Fixed parameters
1.	Uniaxial compression	$E, \nu, \sigma_c(\epsilon_c^p)$	$\sigma_t(\epsilon_t^p), \gamma, \alpha, \phi, e$
2.	Triaxial compression	$\gamma, \alpha, \text{CIF}$	$\sigma_t(\epsilon_t^p), \phi, e, E, \nu, \sigma_c(\epsilon_c^p)$
3.	Notched 3 point bending	$\sigma_t(\epsilon_t^p)$	$\sigma_c(\epsilon_c^p), \gamma, \alpha, \phi, e, E, \nu$
4.	Direct shear	$\phi, e$	$\sigma_c(\epsilon_c^p), \sigma_t(\epsilon_t^p), \gamma, \alpha, E, \nu$
5.	Split tensile	$\max \sigma_t$	$\sigma_c(\epsilon_c^p), \gamma, \alpha, \phi, e, E, \nu$

### Further studies

In order to understand the wider context of this specific study, it is necessary to consider the experimental reinforced concrete slab impact testing, [15, 16] and concrete material model development, calibration and validation work, [12, 7] that has been going on in the Technical Research Centre of Finland (VTT). The primary objective of this research work is to provide a scientifically validated computational analysis tool that enables large scale airplane crash on concrete buildings to be performed. The calibration of the concrete material model parameters is therefore done as suggested in this study using concrete test results from the VTT experimental impact testing program. The validation of the simulation model is then carried out against selected benchmark impact experiments from the same experimental program.

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